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ABSTRACT

Transverse plane pelvis rotations during walking may be regarded as the "first determinant of gait". This would assume that pelvis rotations increase step length, and thereby reduce the vertical movements of the centre of mass—"the pelvic step". We analysed the pelvic step using 20 healthy young male subjects, walking on a treadmill at 1–5 km/h, with normal or big steps. Step length, pelvis rotation amplitude, leg-pelvis relative phase, and the contribution of pelvis rotation to step length were calculated. When speed increased in normal walking, pelvis rotation changed from more out-of-phase to in-phase with the upper leg. Consequently, the contribution of pelvis rotation to step length was negative at lower speeds, switching to positive at 3 km/h. With big steps, leg and pelvis were more in-phase, and the contribution of pelvis rotation to step length was always positive, and relatively large. Still, the overall contribution of pelvis rotations to step length was small, less than 3%. Regression analysis revealed that leg-pelvis relative phase predicted about 60% of the variance of this contribution. The results of the present study suggest that, during normal slow walking, pelvis rotations increase, rather than decrease, the vertical movements of the centre of mass. With large steps, this does not happen, because leg and pelvis are in-phase at all speeds. Finally, it has been suggested that patients with hip flexion limitation may use larger pelvis rotations to increase step length. This, however, may only work as long as the pelvis rotates in-phase with the leg.

1. Introduction

In their classical 1953 paper, Saunders et al. [1] proposed regarding transverse plane pelvis rotation as the first determinant of gait, because it reduces the vertical movement of the centre of mass (CoM). Indeed, without pelvis rotation, if step length is large, the position of the CoM at heel contact will be low (decreasing as a cosine of the angle of the leg with the vertical). Then again, when any specific step length is partially produced by pelvis rotations, the CoM will move down less. Later studies [2,3] have shown that the contribution of pelvis rotations to reducing the vertical displacement of the CoM is only modest, in the order of 10%. Moreover, Kuo [4] argued that a completely flat trajectory of the CoM may not be energy efficient. In any case, the crucial assumption in Saunders et al.'s [1] study is that pelvis rotations actually increase step length.

In 1965, the Ducroquet brothers [5] observed that pelvis rotations increase step length at higher walking speeds only. They

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called this phenomenon *le pas pelvien*, the pelvic step, which occurs from about 3.6 km/h onwards [6,7]. Sessoms [8] published a quantitative analysis of the contribution of pelvis rotation to step length. In healthy subjects, walking at self-selected speed, this contribution was always small ($\leq$3%), and sometimes even negative. In bilateral transtibial amputees who walked slowly, it was always negative.

Bruijn et al. [9] discovered that the phase relationship of pelvis rotations with the sagittal plane movements of the upper leg depends on gait speed. During walking, when the left leg is most forward and the left half of the pelvis most backward, the two would be maximally "out-of-phase", i.e., a phase difference of 180°. When the left leg is in its most forward position, and the left half of the pelvis also, they would be "in-phase", i.e., a phase difference of 0°. In normal walking, Bruijn et al. [9] found that leg and pelvis were relatively out-of-phase at low speeds, and relatively in-phase (i.e., with a phase difference distinctly less than 90°) at speeds of 3.6 km/h and above. Clearly, the "pelvic step" results from two different factors, i.e., the amplitude of horizontal pelvis rotations (which should be large), plus leg-pelvis relative phase (which should be low). Note, however, that these two factors may not be independent.

Inman et al. [10] reported that the amplitude of horizontal pelvis rotations is correlated with step length. In an experimental condition with big steps, Sessoms [8] found that pelvis rotations had a relatively large contribution to step length. On the other hand, Huang et al. [11] observed that walking with big steps not only coincided with a larger amplitude of horizontal pelvis rotations, but also with a decrease of leg-pelvis relative phase. Walking with big steps is an important strategy to avoid landing on the wrong place [12]. On an irregular surface, subjects actually walk with larger steps [13]. The present study focuses on the role of the pelvic step in regulating step length.

In pelvic girdle pain (PGP) [14,15], and lumbar disc herniation [16], pelvis rotations during gait were found to be larger than normal, as was reported for low back pain patients during running [17]. Perhaps, larger pelvis rotations serve to compensate [15,16] for limitations in hip flexion in these patient groups. Children with cerebral palsy, whose legs are difficult to control, also walk with big pelvis rotations [18]. Clearly, pelvis rotations not only play a role in the regulation of step length in healthy subjects, but also in patient populations. Yet, it is still unclear how rotational amplitude and leg-pelvis relative phase determine the contribution of pelvis rotations to step length.

We performed a quantitative analysis of the pelvic step in young healthy adults, who walked on a treadmill at different speeds, with normal and large steps. We calculated pelvis rotational amplitude, leg-pelvis relative phase, and the contribution of horizontal pelvis rotation to step length. We hypothesised (1) that pelvis rotation has a negative contribution to step length at lower speeds, that is to say, when leg and pelvis are relatively out-of-phase; (2) that this contribution is positive from about 3 km/h onwards, when leg and pelvis are in-phase; (3) that the contribution is larger when subjects walk with big steps; and (4) that leg and pelvis are more in-phase when subjects walk with big steps. To determine the relative contribution of amplitude and relative phase to step length, multivariate regression analysis was performed.

2. Methods

2.1. Subjects

We recruited by word of mouth 20 male volunteers, between the ages of 20 and 30, who were self-reportedly healthy, and had no problems with walking. The local Medical Ethical Committee approved the protocol, and subjects signed an informed consent. Before measurement, an orthopaedic surgeon checked their health status. No health problems were found that could interfere with walking.

2.2. Experimental manipulation

Subjects were asked to walk on a treadmill (EN-BO system, Bonte Technology, Amsterdam, The Netherlands), at different speeds (1 through 5 km/h), with normal or big steps. The 10 experimental conditions were offered in random order. Kinematics were recorded during the last 60 s of each 2-min trial.

2.3. Data collection

Kinematic data were recorded at 100 samples/s with a 2 × 3 camera array (OPTOTRAK Certus, Northern Digital Inc., Waterloo, ON, Canada). Clusters of three infrared markers (Fig. 1) were attached with neoprene bands to the pelvis (between the posterior superior iliac spines) and both thighs, and a single marker was attached to the lateral malleolus of each leg. With the cameras on, and the subject standing upright, a pointer with six markers was then used to create virtual anatomical landmarks for the anterior and posterior superior iliac spines.

We used well-established methods in recording and analysing marker movements [9,19]. Still, there is always a chance that markers are not properly attached, or that other experimental errors occur [20]. We included a cluster marker on the thorax (level of Th6), to check if pelvis and thorax would rotate in-phase at the lower, and out-of-phase at the higher speeds [9], and more out-of-phase in walking with big steps [11].

Moreover, in evaluating the contribution of pelvis rotations to step length, we also calculated, by way of comparison, the contribution of the sagittal plane movements of the upper legs. For that reason, we included a single marker on each lateral epicondyle, and pointered each medial epicondyle.

Finally, a reference measurement was taken in the anatomical position to align the coordinate system of each cluster with the

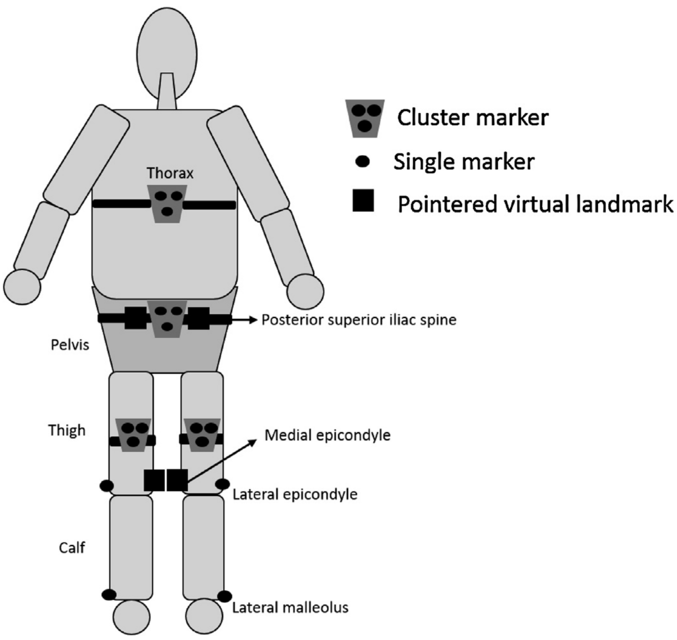

Fig. 1. Cluster markers, single markers, and virtual landmarks that were pointered for kinematic analysis. Note that the anterior superior iliac spines (not depicted here) were pointered also.

global coordinate system (X-axis forward, Y-axis to the left and Z-axis upward).

2.4. Kinematic analysis

2.4.1. Basic gait parameters

Data analysis was performed with custom-made MATLAB 7.14 (MathWorks, Natick, MA, USA) programs. All kinematic data were low pass filtered with a 4th order bi-directional Butterworth filter, cut-off frequency 5 Hz. Heel strike was determined as the time of the most forward position of the lateral malleolus with respect to the pelvis cluster marker. Stride time was defined as the average time between consecutive heel strikes on the same side, and stride length as mean stride time multiplied by treadmill speed.

2.4.2. Amplitude of pelvis rotations

Time series of pelvis rotations were derived from the rotation of the pelvis cluster around the global Z-axis [9]. Rotational amplitude of the pelvis was then calculated as the absolute difference between maximum and minimum per stride.

2.4.3. Relative phase

Time series of leg movements were derived from the sagittal plane movements of the thigh cluster marker. The thorax time series were derived in the same way as for the pelvis. Fourier phase [21] was calculated per segment with respect to the fundamental frequency of the leg. Leg-pelvis and pelvis-thorax relative Fourier phase (RFP) were obtained by subtracting the phase of the cranial segment from that of the caudal one. Then, mean RFP was calculated per subject per trial by using circular statistics [22].

2.5. The contribution of pelvis rotation to step length

Hip joint centres (HJCs) were determined from the positions of the anterior and posterior superior iliac spines by using a validated method [23]. Knee joint centres (KJCs) were calculated as the midpoints between the (virtual) medial and lateral epicondyles. Absolute contributions to step length were then calculated as the sagittal plane distance (m) covered by each segment at heel strike (Fig. 2). For the pelvis, the sagittal plane distance between both HJCs was taken, and for each upper leg, the sagittal plane distance between the HJC and the KJC on the same side. We averaged each segment's absolute contribution to left and right steps. Finally, step length was calculated (cf. 2.4.1), and we expressed each average contribution per subject per trial as a percentage.

2.6. Statistical analysis

All statistical analyses were performed with SPSS 16.0, with significance set as $p < 0.05$. After presenting figures where relevant, we only mention statistically significant effects in Section 3.

To determine the regression of Speed (1–5 km/h) and Step (normal or big) on the variables under study, we used General Estimation Equations (GEEs). GEE [24] is a technique for repeated measures regression analysis, assessing the impact of covariates (here: Speed), factors (here; Step), and their interaction. Non-significant interactions were removed from the analysis.

We used multivariate analysis to assess the impact of the amplitude of pelvis rotations and leg-pelvis relative phase on the pelvis contribution to step length. Firstly, we checked whether pelvis rotation and leg-pelvis relative phase were not too highly correlated (requiring a correlation of less than 0.5). We then performed multivariate regression analysis, and determined the R^2 of the significant variable(s).

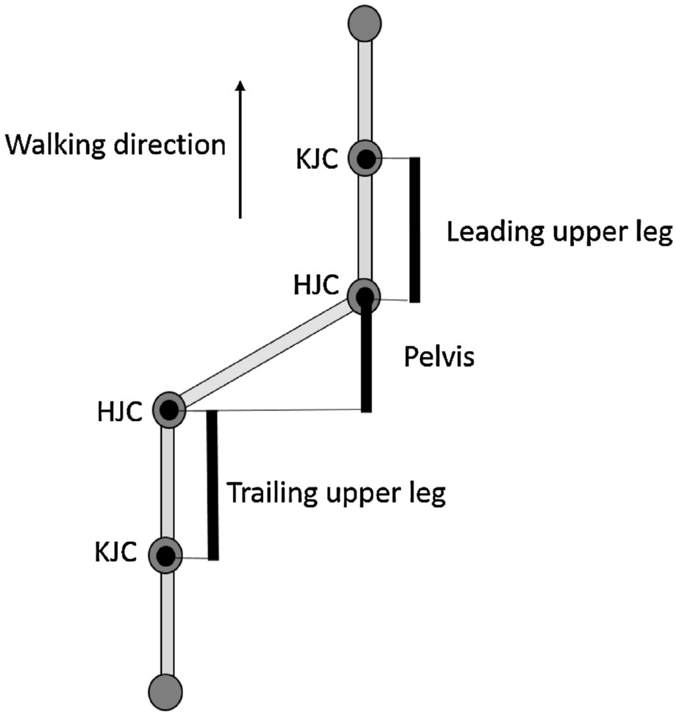

Fig. 2. Contributions to step length. Virtual top view of the pelvis, the upper legs, and the lower legs (all light grey) at right heel contact. Contributions (black bars) are derived from sagittal plane displacements, of the hip joint centres (HJC) for the pelvis, and between the hip joint centres and the knee joint centres (KJC) for the upper legs.

3. Results

3.1. Stride length

Stride length increased with speed (Table 1, cf. Fig. 3A), and was larger when subjects were instructed to take big steps. With big steps, stride length increased less with speed than with normal steps.

3.2. Pelvis rotation amplitude

Visual inspection (Fig. 3B) revealed that, with normal steps, pelvis rotational amplitude first decreased with speed, and then increased from 3 km/h onwards. Overall, GEE revealed a decrease of pelvis rotation amplitude with speed, but with big steps, pelvis rotation amplitude was larger, particularly so at the higher speeds (Table 1).

3.3. Relative phase

Leg-pelvis relative phase (Fig. 3C) was larger with normal than with big steps, and decreased with speed. Leg and pelvis were clearly in-phase at the higher speeds. GEE confirmed the effects of Speed and Step, and revealed that the effect of Step was particularly present at the lower speeds (Table 1).

With increasing speed, pelvis-thorax relative phase (Table 1) went from in-phase to more out-of-phase. It was larger with big steps, but not at the highest speeds.

3.4. Contributions to step length

With normal steps, the pelvis contribution to step length increased from −2.5% at 1 km/h, through 0% at 3 km/h, to +1.8% at 5 km/h (Fig. 4A). With big steps, the contribution was always positive, increasing from 1.0% to 2.8%. A GEE (Table 1) revealed an increase of the pelvis contribution with speed, and with step size. The effect of Step was smaller at the higher speeds.

The contributions of the upper legs were clearly bigger than those of the pelvis (Fig. 4B and C). Upper leg contributions ranged from about 18% to 28%. In GEEs, these contributions decreased with speed and also with big steps, particularly at the lower speeds (Table 1).

Table 1
Effects on kinematic variables of Speed, Step, and their interaction (GEEs).

	Intercept		Speed		Step		Speed × Step	
	P	*B*	*P*	*B*	*P*	*B*[a]	*P*	*B*[a]
Stride length (m):								
	<0.001	0.53	<0.001	0.19	<0.001	0.55	<0.001	−0.04
Pelvis rotation amplitude (°):								
	<0.001	16.97	0.002	−1.51			0.002	1.75
Relative phase (°):								
Leg-pelvis	<0.001	110.14	<0.001	−13.3	<0.001	−48.77	0.001	6.54
Pelvis-thorax	0.382	−8.09	<0.001	25.73	0.01	28.09	0.01	−7.42
Contributions to stride length (%):								
Pelvis	<0.001	−3.45	<0.001	1.08	<0.001	3.98	<0.001	−0.66
Upper leading leg	<0.001	28.10	<0.001	−1.82	<0.001	−5.60	<0.001	1.47
Upper trailing leg	<0.001	28.24	<0.001	−1.86	0.001	−6.03	0.001	1.53

[a] For big steps.

3.5. Multivariate regression

The Pearson correlation between the amplitude of pelvis rotations and leg-pelvis relative phase was small, −0.32. A multivariate regression analysis of the contribution of pelvis rotation to step length, revealed no significant regression of pelvis amplitude ($p = 0.06$), but the regression of leg-pelvis relative phase was clearly significant ($p < 0.001$), with an R^2 of 0.60.

4. Discussion

We studied the contribution of pelvis rotations to step length in young healthy adults, walking at different speeds on a treadmill, with normal or big steps.

Several findings of earlier studies were confirmed. For instance, we found a U-shaped effect of walking speed on pelvis rotation amplitude when subjects walked with normal steps [9,25], but larger amplitudes and no U-shape when subjects walked with big steps [11]. Moreover, the pelvis rotated relatively out-of-phase with the upper leg at the lower speeds, but more in-phase at higher speeds [9,11]. Finally, the thorax rotated in-phase with the pelvis at lower, but more out-of-phase at the higher speeds [7,21], or with big steps [11]. Still, we found this effect of big steps at the lower speeds only, contrary to Huang et al. [11], who reported it for all speeds. Perhaps, subjects can use different trunk strategies to increase stride length. Note, however, that it is impossible to exclude technical error with complete certainty when using

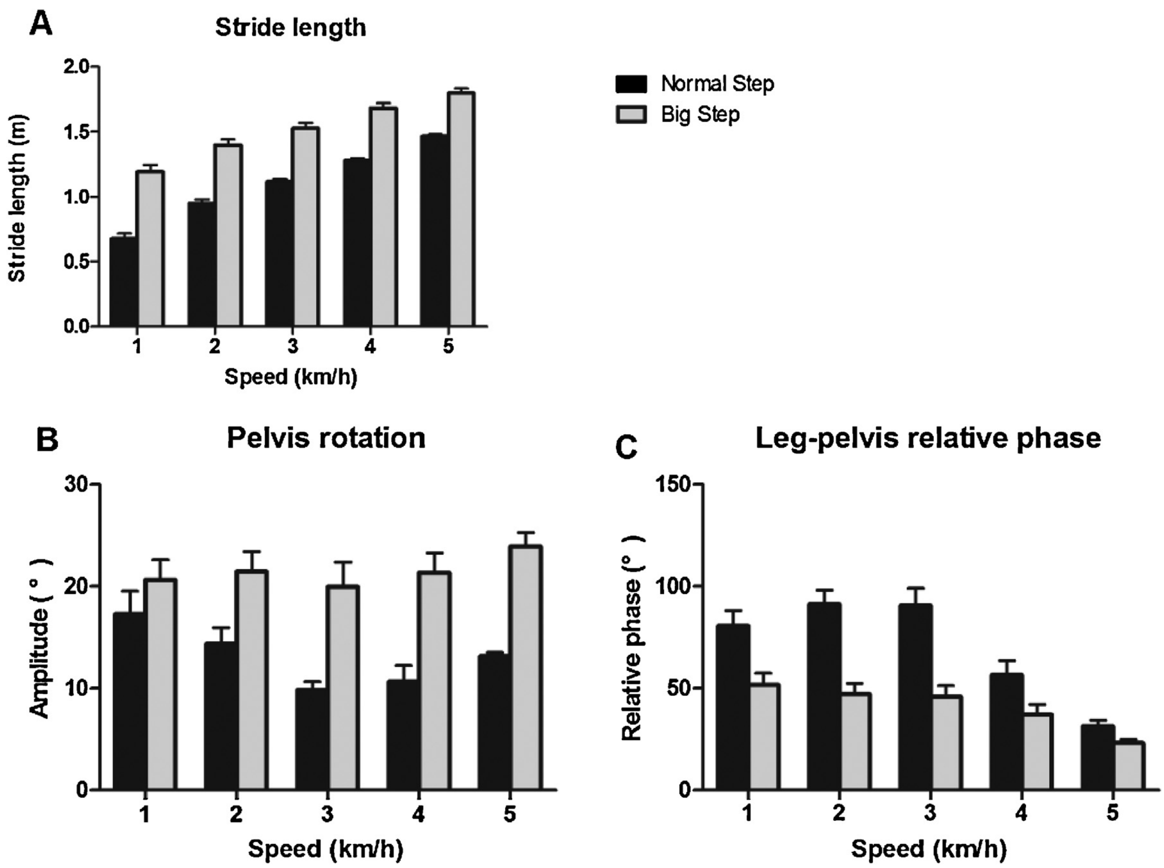

Fig. 3. Stride length (A), amplitude of pelvis rotation (B), and leg-pelvis relative phase (C) during gait at 1–5 km/h (horizontal axis), with normal steps (black) or big steps (grey). Error bars represent standard errors.

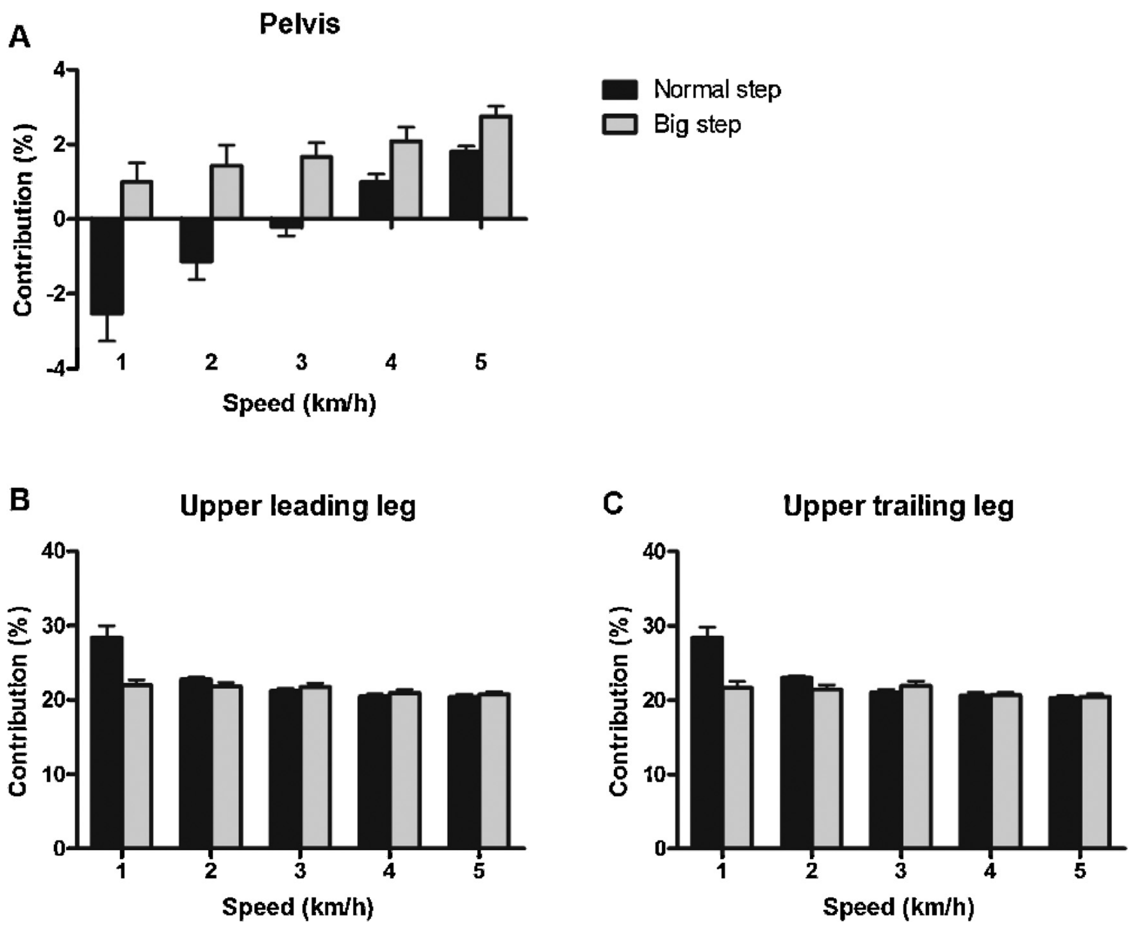

Fig. 4. Contribution to step length of the pelvis (A), the upper leading leg (B), and the upper trailing leg (C) during gait at 1–5 km/h (horizontal axis), with normal steps (black) or big steps (grey). Error bars represent standard errors.

kinematic methods. Still, the overall correspondence with previous findings suggests that wrong marker placement or other experimental error played no major role in the present study.

The novel result of the present study was found in slow walking with normal steps, i.e., when leg-pelvis relative phase was high. In that situation, pelvis rotations had a negative contribution to step length. At higher speed, with low leg-pelvis relative phase, the contribution was positive. This pattern of results is what our first and second hypothesis predicted. Sessoms [8] reported negative contributions of pelvis rotation to step length in some healthy subjects who walked at self-selected speed. In that study, speed was not manipulated with any precision; nor was leg-pelvis relative phase calculated. In our own multivariate analysis, leg-pelvis relative phase was found to "explain" about 60% of the variance of the pelvis contribution to stride length. Regression does not prove causation, but leg-pelvis relative phase appears to be a crucial factor in the quantitative determination of the pelvis contribution to step length.

Saunders et al. [1] argued that pelvis rotations reduce the up-and-down movements of the CoM. At the lower speeds, this appears to be incorrect for walking with normal steps. Given step length, out-of-phase pelvis rotations will force the legs to contribute more to step length, and, thus, to spread more in the sagittal plane. This will lead to an increase, rather than a decrease of vertical CoM movements, which indirectly agrees with Kuo's [4] suggestion that the vertical trajectory of the CoM should not be too flat. On the other hand, at higher speeds, with leg and pelvis more in-phase, pelvis rotations indeed decrease vertical CoM movements, as suggested in the original paper by Saunders et al. [1]

Given that pelvis rotation was labelled as the "first determinant" of gait [1], it is perhaps surprising to see that the actual contribution of pelvis rotation to step length is quite small. In the present study, it ranged, with normal steps, from −2.5% at 1 km/h to about +2% at 5 km/h. These values were up to 20 times smaller than those of the leading or trailing upper leg. Still, our results are close to those of Sessoms [8], who reported an average contribution in healthy subjects of 0.3%. Nevertheless, a small contribution is not necessarily an unimportant one. As alluded to in the Introduction, the pelvic step may be important when subjects walk with big steps, or when subjects compensate for pathological limitations.

When subjects walked with big steps, the pelvis contributed more to step length, from 1% at 1 km/h to 3% at 5 km/h. Sessoms [8] also reported a larger contribution in big step conditions, even up to 10%. Furthermore, in the present study, leg-pelvis relative phase was lower in conditions with big steps. Together, these results are what our hypotheses 3 and 4 predicted. When subjects deal with irregular terrain, it could be a matter of life or death to produce the right step length [12]. More to the point, to make large steps may require fine-tuning of the pelvic step, and the pelvic step appears to depend on the control of leg-pelvis relative phase. The role of leg-pelvis relative phase in the control of step length is an important topic for further research.

It has been suggested that patients with pelvic girdle pain [15], or lumbar disc herniation [16], walk with larger pelvis rotations to compensate for the limitation of their hip flexion. If the present study is also valid for locomotor pathology, the implied increase in step length would require a concomitant reduction of leg-pelvis relative phase. However, in Huang et al.'s [16] study, there was no significant difference in leg-pelvis relative phase between healthy controls and patients with lumbar disc herniation. For the lower speeds, this sheds serious doubt on the idea that these patients walk with larger pelvis-rotations in order to increase step length. Therefore, why patients with pelvic girdle pain, or with lumbar disc herniation, walk with large pelvis rotations, is another important question for research.

The major limitation of the current study is that we worked with a relatively small group of healthy subjects. Replication with patient groups will certainly be needed. We used a treadmill, which allows for systematic manipulation of speed. Sessoms [8] studied overground walking, and manipulated step length with marks on the floor. Both methods have their advantages [26,27], and leg-pelvis relative phase may be different between overground and treadmill walking. Finally, we did not manipulate leg-pelvis relative phase, and, therefore, our study does not allow for causal inferences about its effects on step length.

We conclude that both the amplitude of transverse plane pelvis rotations, and their relative phase with the movements of the upper leg, need to be taken into account in any analysis of the pelvic step. At the lower walking speeds, with normal steps, pelvis rotations had a negative contribution to step length, probably because the pelvis rotated relatively out-of-phase with the leg. Above 3 km/h, more in-phase pelvis rotations contributed positively to step length. When subjects walked with large steps, the pelvis rotated more in-phase with the legs at all speeds, and the contribution of pelvis rotation to step length was larger. Overall, the contribution of pelvis rotation to step length was small. In fact, the relative timing of pelvis rotations with respect to the leg appears to be a more important variable in the control of step length than the amplitude of pelvis rotations per se.

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Conflict of interest statement

None of the authors of this paper had any conflict of interest that could inappropriately influence (i.e., bias) the presented work.

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